Co-combustion of Wood in Coal-Fired Large-Scale Power Plants

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Glossary

Ash Residue obtained after combustion of a fuel.

Biomass From a scientific and technical point of view, biomass is defined as material of biological origin, excluding material embedded in geological formations and/or transformed to fossil.

Bioenergy Bioenergy is defined as energy from biomass.

Co-combustion Simultaneous combustion of biomass and fossil fuels within the same combustion device.

Combustion Full oxidation of a fuel.

Solid Biofuel Solid fuel produced directly or indirectly from biomass.

Thermochemical conversion Heat-induced conversion of biofuels into energy carrier and/or energy.

Definition of the Subject

Due to the introduction of the CO_2 emissions trading, the co-combustion of wood in coal-fired large-scale power plants gains more and more importance within the energy industry. Co-combustion of biomass in coal-fired power plants means the utilization of solid biofuels in existing hard coal- or lignite-fired power plants or combined heat and power (CHP) plants for the replacement of fossil fuel energy. (Parts of this paper are retrieved from [1].) For detailed citation see [1].

This option is particularly characterized by the following benefits:

1. Highly efficient electricity provision from biomass compared to a electricity production in small-scale units; this allows conserving natural resources, which can even be improved by additional extraction of heat in combined heat and power generation plants,
2. High greenhouse gas (GHG) reduction efficiency by direct replacement of coal as the fossil energy source with the highest specific greenhouse gas emission,
3. Relatively low investments for the prevalent co-combustion rates of 3–10% of the boiler capacity.

Therefore, the objective of the following explanations is it to provide a comprehensive analysis of the technical effects on the power plant processes by different co-fired solid biofuels. Subsequently, a special focus is put on the experiences with co-combustion of natural wood in three large-scale coal-fired power plants in Berlin/Germany. Finally, appropriate conclusions are drawn.

Introduction

Of all renewable sources of energy, biomass contributes by far most to cover the demand of energy in Germany and globally. In Germany, for instance, approximately 70% of the total primary energy from renewable sources of energy is derived from biomass; for the generation of heat, biomass (mainly wood) takes a share of almost 94%, for the biofuels this is 100%, and for electricity, it ranks second (28%) behind wind (40%).

Approaches of a combined use of fossil and renewable sources of energy particularly apply for biomass, for example, adding a mixture of solid biofuels to fossil fuels or feeding biogas into natural gas distribution systems as well as co-combustion of biomass in large-scale power plants. This combined utilization with a limited share of renewable energies is mainly used

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for technical reasons so that the high efficiency of the technical installations achieved with fossil standard and regular fuels as well as their life cycle will not be compromised.

The latter particularly applies to biomass co-combustion in large-scale combined heat and power (CHP) plants, where a high efficiency for electricity generation exists due to advanced steam parameters. In addition, hard coal or lignite is directly replaced by the CO_2-neutral biomass. Therefore, co-combustion of solid biofuels in coal-fired power plants is particularly efficient from a climate protection point of view due to direct and immediate replacement of fossil fuel energy with high specific CO_2 emissions (i.e., coal). In contrast to that, pure biomass-fired power plants primarily displace electricity from the local electricity mix and thus electricity provided with a high percentage of low-CO_2 electricity from, e.g., windmills or PV systems. The moderate additional investments and short transport distances for the manageable quantities account for other benefits of biomass co-combustion in a limited scope of approximately 3–5% of the boiler capacity. Such co-combustion of biomass in conventional coal-fired power plants is influenced by a series of ancillary conditions, which will be briefly discussed below.

The share of solid biofuels in the total thermal performance of a conventional power plant fired with hard coal or lignite is limited by the amount of biomass, which can be used in the combustion system without significant disadvantages to be expected (e.g., corrosion, emissions, flow conditions). For instance, usually a share of 10% of biomass energy referring to the amount of fossil fuel energy resp. the installed thermal capacity should not be exceeded to keep measures of adjusting the existing power plant to such changed conditions as low as possible. However, higher percentages are possible for lignite-fired systems for firing systems converted from lignite to hard coal with flue gas recirculation and for fluidized bed systems. Additionally, the biomass flow, which can be used for co-combustion, is also limited by the quantity of biomass fuels, which can be provided at a certain power plant site for economic reasons. For example, the upper performance limit of biomass provision under Central European conditions would be approximately 50–100 MW of biomass fuel capacity. For higher capacities, the size of the required catchment area will increase so that transport effort, which is mostly handled by road due to infrastructural constraints, will increase too much and thus the procurement costs for biomass will become too high.

Against this background, the coal-fired power plants coming into consideration for co-combustion of solid biomass are on the one hand comparably “small” combined heat and power (CHP) generation plants normally operated by public utility companies in a capacity range below approximately 100 MW of electric power. On the other hand, also the larger block-unit power stations with installed electrical capacities of 500–1,000 MW come into consideration. Facing the comparably large installed electric (and thus also thermal) power in the scope of large-scale power stations, even percentages of co-firing of 5–10% mean truly significant quantities of solid biomass, so that for the large-scale biomass co-firing, there is no need to be worried about higher shares of biomass in the firing heat capacity.

The utilization of biomass in existing large-scale coal-fired power plants for the generation of electricity has a number of advantages compared to the generation of electric energy in smaller plants exclusively fired with biomass.

- The significant power plant capacity available in Central Europe for generating electricity from coal results in a high potential for the utilization of biomass. From a technical point of view, this potential is quickly available; limitations only exist due to the fact that principally not all locations of large-scale power plants are qualified for co-combustion of biomass (e.g., due to logistic limitations). Even with a comparably small share of biomass referring to the overall installed thermal capacity resp. to the overall used fossil fuel energy, a huge amount of solid biomass can be used.
- Compared to smaller plants exclusively fired with biomass, the efficiency of electricity generation in large-scale power plants normally is significantly higher due to a higher technical effort possible in large-scale plants due to economic reasons.
- In case of seasonal nonavailability or in case of supply bottlenecks for solid biofuels due to weather conditions, electricity generation can be ensured by

the basic fuel of coal (i.e., high security of supply with high fuel flexibility).

- The additional investment required for the realization of biomass co-combustion is relatively low because only the additional equipment is counted for.

The substitution of the fossil fuel of coal by solid biofuels makes the acquisition of an according quantity of emission permits dispensable, thus creating the financial scope for the co-combustion of biomass.

Principally, besides solid biofuels (like wood) also, other biomass fractions available in a corresponding quantity and homogeneity (e.g., sewage sludge) can (and will) be co-fired in existing coal-fired power plants along with solid biomass such as wood and straw. Thus co-combustion is also suitable for types of biomass which from a combustion point of view are rather problematic and for which revenues for disposal is paid to some extent.

Biomass Processing

The required processing of the solid biofuel for co-combustion in existing power plants depends on the type of biomass and on the firing system technology (see [1–31]).

The solid biofuel co-fired in large-scale power plants should principally be free of foreign substances (e.g., rocks, metal parts) so that downstream conveying equipment, processing units (e.g., shredders for coarse matter), or dosing units will not be affected.

Drying of the biomass may possibly be required. While this, from a combustion point of view, is normally not required for wood and straw, it could however be advantageous from an energetic point of view. This particularly applies if waste heat can be utilized for this purpose, which before that had not been used.

Due to some impurities within some solid biofuels (e.g., chlorine in straw) problems can be expected during the combustion within the power plant (e.g., corrosion). For example, one measure to prevented such problems is the "washing" the fuel if the impurities are water-soluble (which is the case for the chlorine within the straw). In this process, some impurities (e.g., chlorine, alkalines) are washed out of the solid biofuel with water. Because of this, the biofuel can be used within the firing system of the power plant with probably less problems. However, the negative aspect is the high-energy input for the practical realization of such considerations.

The particularities for dust firing and fluidized bed systems with respect to processing of the biofuels to be co-combusted are discussed below.

Processing for Dust-Fired Systems

Dust firing requires extensive milling of the biomass used (e.g., wood-like woodchips, herbaceous biomass like straw bales) to achieve a complete burnout. Cutting mills, hammer mills can be used for this purpose.

The wood particles milled with a cutting mill have a rather cubic shape, while particles from herbaceous biomass (e.g., straw, hay) have the shape of oblong, rectangular platelets. The demand of electric energy needed for such milling is increasing with declining particle size. In average, the energy demand is between approx. 0.8 and 2% of the calorific value of the biomass, when cutting mills are used with screens of a mesh size between 2 and 6 mm. Using a hammer mill, the energy demand can be reduced to 0.5–1% of the calorific value. Increased water content of the fuel principally leads to higher energy consumption; the energy demand is especially increasing with water contents of more than 10–20%. For straw, for example, more than 8% of the calorific value is needed for milling in a cutting mill with a mesh width of 2 mm and a water content of 30%. This energy demand can be reduced by previous torrefaction.

Processing for Fluidized Bed Systems

Wood can be used in fluidized bed systems as woodchips without further milling. For example, maximum piece sizes for wood in circulating fluidized bed systems are around 60 mm and in stationary fluidized bed systems around 100 mm. For herbaceous biomass, the bales have to be opened to get loose stalks and the stalks need to be cut to lengths of around 10–30 cm. Thus, there are virtually no differences to exclusive biomass combustion with regard to fuel dimensions.

Fluidized bed systems therefore require only little processing of the fuel to be fired. In addition, they are resistant to increased water content of fuels and/or low calorific values, as well as fluctuations in water content.

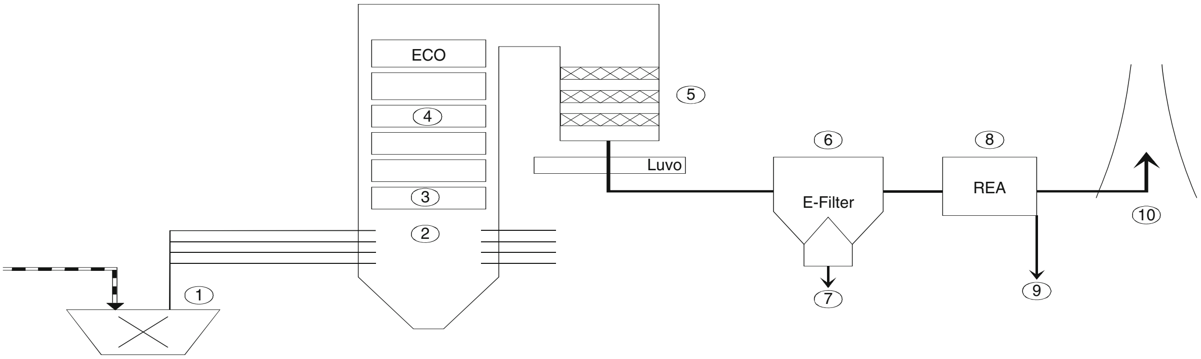
Co-combustion in Dust-Fired Systems

The resulting mass and volume flows and their changes compared to exclusive firing of coal, as design fuel, is of fundamental importance for the possibility of co-combustion of biomass in existing dust fired systems (see [1–31]). Also, the existing facilities for transport and processing of the fuel must be suitable with respect to the changed fuel volume flow. Beside this, they necessarily have the required capacity. In addition, the change of the flue gas volume flow has to be evaluated as this is influenced by the different water content in the solid biofuel resp. the coal and by the different quantities of reaction water from the oxidation of the hydrogen contained in the fuel. This will significantly affect the behavior of heat transfer and retention time inside the steam generator and the function of the downstream flue gas cleaning equipment. Figure 1 outlines the effects of the co-combustion to the components of a dust-fired power plant based on hard coal. They are discussed below for the co-combustion of wood and herbaceous biomass. In addition, sewage sludge will be considered as an example because, until now, this fuel of biogenic origin has gained the largest importance in practical realization.

Fuel and Flue Gas Volume Flow

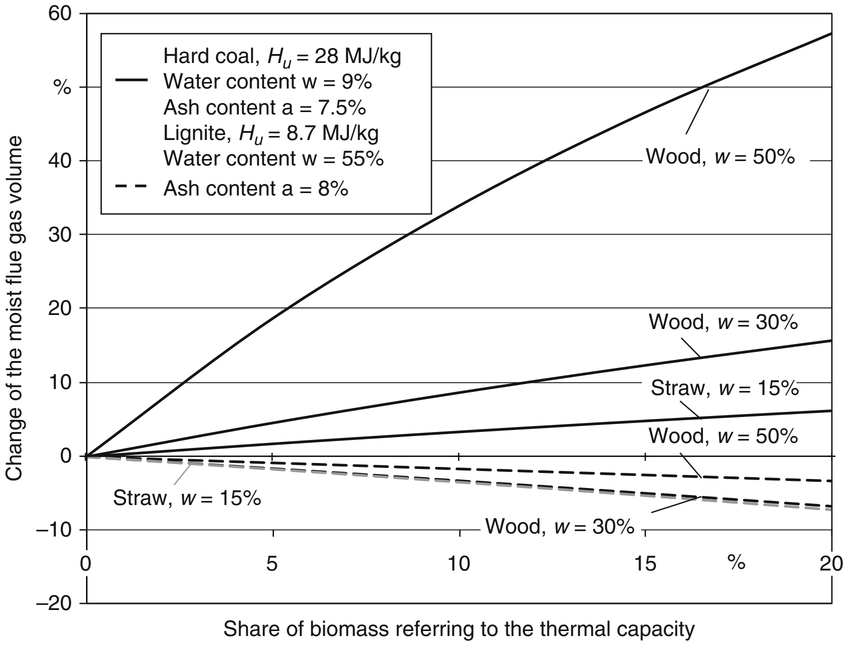
From fuel supply to fuel input, the fuel volume flow is strongly increasing by the addition of wood and herbaceous biomass to the coal (Fig. 2) (see [1–31]). This is due to the significantly lower heating value of the solid biofuels compared to coal and, therefore, relatively larger biomass flow (also compared to coal) to achieve the same energy input. For example, a capacity share of 10% of co-combustion of straw in hard coal dust-fired systems will lead to doubling of the total fuel volume flow. Therefore, both milling of the biomass and conveying of the solid biofuel to the combustion chamber should be carried out separately. In this process, in most cases, the coal-grinding mills cannot be used for the biomass to be co-fired due to the different structure of the solid biofuel and the coal. Therefore, separate grinding mills are usually required for this.

The co-combustion of biomass in coal-fired systems will change the gas flow inside the boiler only to a small extend. Both, the fed combustion air and the flue gas volume remain constant largely. If, for example, dry wood or straw is used in a hard coal–fired system, the moist flue gas volume flow will change by maximum 1% with a share of 10% biomass of the



1 Mill: Capacity, attrition
2 Combustion chamber: Slagging
3 Super heater: Corrosion
4 Heat exchanger: Dirtiness, erosion
5 Flue gas denitrification system: Deactivation, capacity, erosion
6 Electrostatic precipitator: Capacity
7 Ash: Utilization
8 Flue gas desulphurisation plant: Capacity
9 Products of the flue gas desulphurisation plant: Utilization
10 Flue gas: Emissions

Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 1
Possible effects and affected plant components with co-combustion (according to [1])



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 2
Change of the moist flue gas volume flow with biomass co-combustion [1]

installed thermal capacity, depending on the biomass and its humidity (Fig. 2). Even with very moist biomass (e.g., bark, fresh-cut grass), the increase of flue gas caused by this will remain in the area of a few percent.

By co-combustion of biomass with hard coal, the water content of the sewage sludge will influence the fuel-mass flow as well as the flue gas volume flow. While for a thermally dried sewage sludge with 95% dry matter (TM) with a 10% share of sewage sludge referring to the overall installed thermal capacity, the fuel mass flow will increase by 18%, the increase with mechanically well dehydrated sludge with 45% dry matter (TM) is approx. 70% already with the same percentage of thermal capacity.

This results in a high demand of adaptation for the conveyor technology, the mills and the feeding system for the fuel into the boiler, when disproportionately large quantities of water are entered together with the sewage sludge into the system. A similar situation is also given to the flue gas treatment system. The increased flow speed of the flue gas due to the increased volumes leads to a change of the heat transfer as well as an increase of the pressure losses; furthermore, it also affects the cleaning efficiency of the flue gas–treatment system.

If however the main and the additional fuel have nearly the same content of water, the required changes are low. Therefore, co-combustion of moist biomass (e.g., humid wood, dehydrated sewage sludge) with raw lignite (water content approximately 50%) is a suitable and very promising option. The humid flue gas volume is slightly decreasing in this process. Dry biomass or dried sewage sludge can be fired with hard coal with a water content of approximately 7%. Moist wood would not lead to an acceptable increase of volume flow with higher shares referred to the thermal capacity. For the usually realized low percentages of co-combusted referred to the thermal capacity, however, also mechanically dehydrated sewage sludge can be used in hard coal–fired plants usually without any major problems.

Combustion Process

The biofuel needs to be appropriately milled to ensure complete combustion within dust-fired systems (see [1–31]). The maximum particle size for safe ignition and complete burn-off – for example, in a 0.5 MW pilot plant – is approximately 6 mm for straw and approx. 4 mm for Miscanthus (mesh diameter of mill) due to its woody structure. Grinding of wood is required between 2 and 4 mm for co-combustion in coal dust flames. In plants with a higher thermal capacity of up to several 1,000 MW, also coarser biomass particles can principally be co-fired due to the longer retention times. In a large-scale power plant, for example, straw with stalk lengths up to 10 cm was completely burned up.

In addition, significantly coarser fuel particles can be used in dust-fired systems than for coal due to the high volatile content of the solid biofuels. In this process, herbaceous biomass is more reactive than woody biomass and thus requires less fine grinding. So, there is no need to dry the solid biofuels for water contents of up to 50%.

The significantly coarser grinding of the biomass particles affects the combustion process. This is exemplarily shown in Fig. 3 in a coal dust flame and coal dust/biomass flame, respectively. The delayed ignition of the coarse straw particles can be seen for the run of the medium oxygen concentration along the combustion path. After ignition, the oxygen is used up faster and the combustion after ignition until burn-off is faster than for coal.

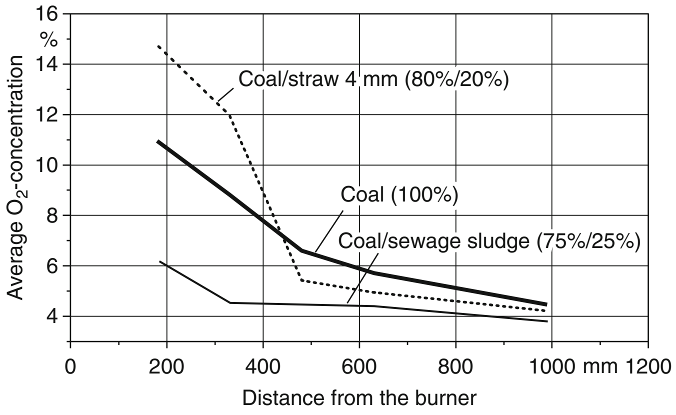
Slagging and Fouling

Due to the lower melting points of the biomass ash particles (especially for straw) compared to coal ash particles, there is a higher risk of slagging in the area of the combustion chamber (see [1–31]). The effects of low melting temperatures are different for dry deashed and molten deashed firing equipment. While low melting temperatures can be absolutely desirable for slag-tap furnaces, a lower melting temperature in dry furnaces can lead to slagging in the combustion chamber and especially in the area of the burner, which will affect operation and does not allow a continuous and safe operation any more.

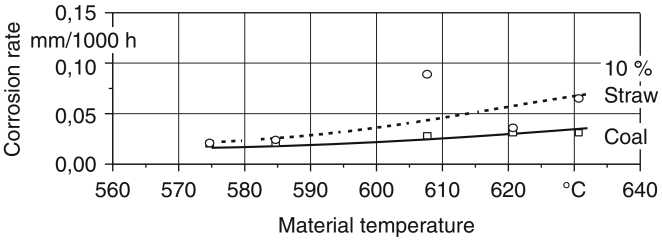
Fouling and slagging on the convective heating surfaces resulting from the solid biofuel increases with growingly lower melting points of the biofuel used. Examinations at a 0.5 MW research plant however show that the fouling rate for the co-combustion of straw was only insignificantly higher than for firing of coal which is rather less prone to pollution. Furthermore, the dust layer resulting from the combustion can be easily cleaned. The properties of the coal ash therefore dominate the ash behavior of the ash mixture if the share of biomass within the fuel mixture is not too high. If however larger straw particles will deposit, which are incompletely burned off, they lead to corresponding slagging due to their low melting point of straw ash.

Corrosion and Erosion

Herbaceous biomass (e.g., straw) has a significantly higher chlorine content compared to coal and wood (see [1–31]). This can lead to increased high-temperature corrosion with corresponding abrasion of the surfaces of the heat exchanger. The heating surfaces of the superheater with their high steam and



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 3
Combustion process of a mixed biomass/coal flame (according to [1])



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 4

Corrosion rates for co-combustion of straw in a dust-firing system with an electric capacity of 130 MW, exemplary for the material X20CrMoV121 (according to [1])

flue gas temperatures are affected first and foremost (Fig. 4). All in all, however, the measured corrosion rates at the heating surfaces of the coal dust-fired equipment seem to be acceptable compared to exclusive firing of coal if the percentage of biomass in the total firing heat capacity is limited to small quantities, as shown.

Due to the low share of ash referring to the fuel mass in most biomasses discussed for co-combustion, there will be almost no increase of erosion (i.e., material removal by abrasive flue gas components) to equipment parts, where the dust-loaded flue gas volume flow is passing through.

The chlorine content of sewage sludge is in the range of the chlorine contents of coal. Therefore, increased high-temperature corrosion cannot be expected in case of co-combustion of coal with sewage sludge. However, increased pollution and erosion may result in the area of the convective heating surfaces.

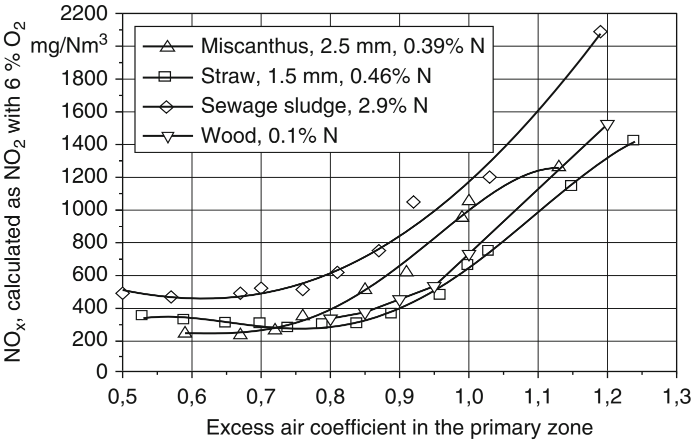
Emissions

The co-combustion of wood and herbaceous biomass in coal-fired power plants leads to a reduction of the main harmful substances in the raw flue gas prior to flue gas cleaning (see [1–31]). Sulfur dioxide (SO_2) is reduced, on the one hand, by the integration of sulfur into the ash and, on the other hand, by dilution, because the biomass fuels shows in average significant lower sulfur content than coal. Also, nitrogen oxide (NO_x) can reach lower values due to biomass-specific advantages in combustion kinetics even if there is not much change for the total nitrogen content in the fuel. Beside this, the carbon monoxide (CO) emissions do not increase when the biomass is sufficiently milled.

Due to the high content of volatile matter, biomass is particularly suitable for the application of nitrogen oxide (NO_x) reduction processes such as air and fuel grading. Although for straw, the fuel nitrogen related to the calorific value approximately corresponds to the value of coal. Thus, the higher release of products of pyrolytic degradation and volatile nitrogen compounds produce less nitrogen oxide in the process of thermochemical reaction. Figure 5 therefore shows as an example the NO_x emissions identified in a pilot plant for a fuel mixture of 25% of particular biomass and 75% of hard coal (each time related to the total installed thermal capacity). Thus, approximately the same NO_x emissions result independently of the nitrogen content in the biomass.

Therefore, the co-combustion of biomass in dust-fired systems does not place any requirements on the nitrogen content of the biomass. Also, higher nitrogen concentrations in the biofuel can be managed by measures of firing technology.

The co-combustion of sewage sludge however leads to an increase of the concentration in the raw flue gases for specific substances such as sulfur dioxide, nitrogen oxides, or volatile heavy metals, which may require additional downstream flue gas cleaning stages. The pollutant concentrations within the flue gas depends on the percentage of sewage sludge in the total fuel throughput, the percentage of sulfur or nitrogen relating to the calorific value and the conversion rate. In case of co-combustion of thermally dried sewage sludge with hard coal, for example, the nitrogen input of the sewage sludge relating to the calorific value is approximately 7 times larger than that of coal. For fuel sulfur, the relation is about 3.3.



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 5
Nitrogen oxide (NO$_x$) emissions with different excess air coefficients in the primary zone for different types of biomass with fuel mixture of 25% biomass and 75% coal, each time related to the thermal fuel capacity (according to [1])

The conversion rate of sulfur to sulfur oxide (SO_2) is independent of the percentage of sewage sludge and is approximately 90%; this results in an increase of the SO_2 emissions proportional to the percentage of the sewage sludge. The high content of calcium oxide (CaO) of the sewage sludge ash does not lead to a reduction of the SO_2 emissions. This can be explained by an inactivation of the calcium oxide by the surface fusion with the high temperatures in the dust firing.

With corresponding reduction measures of air and fuel grading in the combustion chamber, the nitrogen oxide emissions of the sewage sludge co-combustion are comparable to those with exclusive firing of coal. The high nitrogen percentage in the fuel, however, should be considered for the burner design and the air distribution in the particular combustion chamber.

The chlorine contents related to the calorific value for hard coal and municipal sewage sludge is approximately in the same range; a significant increase is possible only for industrial sludge. Generally, no increased values are measured also for the PCDD/PCDF emissions, which can be formed in the fuel in the absence of chlorine.

Flue Gas Denitrification

By analyzing the effects of biomass co-combustion to the denitrification in DENOX plants, it must be differentiated between high-dust and low-dust configuration (see [1–31]).

Altogether for a low-dust configuration, the possible effects (e.g., catalyst deactivation) to the operation of a DENOX plant are less compared to the high-dust configuration due to the previously realized flue gas cleaning with the electrostatic precipitator and the flue gas desulfurization system (REA); therefore, this configuration offers advantages for the co-combustion compared to the high-dust configuration.

In particular, for a configuration of the DENOX system in the high-dust area as usually realized in hard coal dry-firing systems, the catalyst is endangered by possible deactivation during co-combustion; this particularly applies if straw is used. Different mechanisms can be involved in this deactivation process. For example, the catalyst can react with potassium and sodium. Therefore, limit values of the alkaline percentage are specified by manufacturers of DENOX-catalysts (K_2O and Na_2O below 4% by weight of ash), which however – depending on the coal used – can already be reached with small fractions of straw. Additionally, a blockage of the pores of the active catalyst cells may result due to alkaline and alkaline earths. In addition, phosphor may contribute to a toxification of the catalyst. Such damage can be prevented by arranging the catalyst behind the flue gas desulfurization system (REA) (i.e., low-dust configuration). This problem does not occur in lignite firing systems, where primary measures are used for denitrification. In general, significantly less problems can also be expected for wood due to the considerably lower content of problematic substances.

For the high-dust configuration, the relatively high ash content of sewage sludge can lead to pollution and to erosion on the DENOX-catalyst. Due to the high nitrogen fraction, the NO_x-concentrations in the raw flue gas can increase. Due to this, they need to be subsequently reduced in the DENOX system. Specific substances (e.g., arsenic, phosphor) may lead to a deactivation of the catalyst here.

Flue Gas Desulfurization

The low content of sulfur of most solid biofuels leads to a relief of the flue gas desulfurization plant (REA) (see [1–31]). The input of other flue gas substances however can possibly affect the function of the flue gas desulfurization plant or additionally burden it; this also may result in a limitation of the biomass share. This particularly applies to the chlorine input into the flue gas desulfurization plant.

Next to sulfur, also a number of other flue gas components are deposited in the flue gas desulfurization plant (REA); these are, e.g., the volatile ash components in the flue gas such as mercury, arsenic, lead, and other heavy metals. They can be found in the REA residuals (e.g., REA gypsum); therefore, their quality has to be inspected prior to marketing. For wood and herbaceous biomass considered here, the concentrations of such substances can be disregarded compared to coal.

The sulfur contained in the sewage sludge however significantly exceeds the sulfur content of coal in most cases. Therefore, the desulfurization plant has to have a sufficient capacity to safely adhere to the legal emission limits. For example, for a 25% co-firing of sewage sludge within a coal-fired power plant, the SO_2 amount to be bonded within the flue gas desulfurization plant will increase by the factor 1.6.

Ash Formation and Utilization

When considering the possible effects of co-combustion of biomass in coal-fired power plants, also the results for ash formation and ash utilization has to be taken into consideration (see [1–31]).

Ash formation. The small ash fractions of the soli biofuels wood and straw relieve the facilities for dust separation. Altogether, less ash accrues in case of co-combustion of wood and herbaceous bioenergy sources.

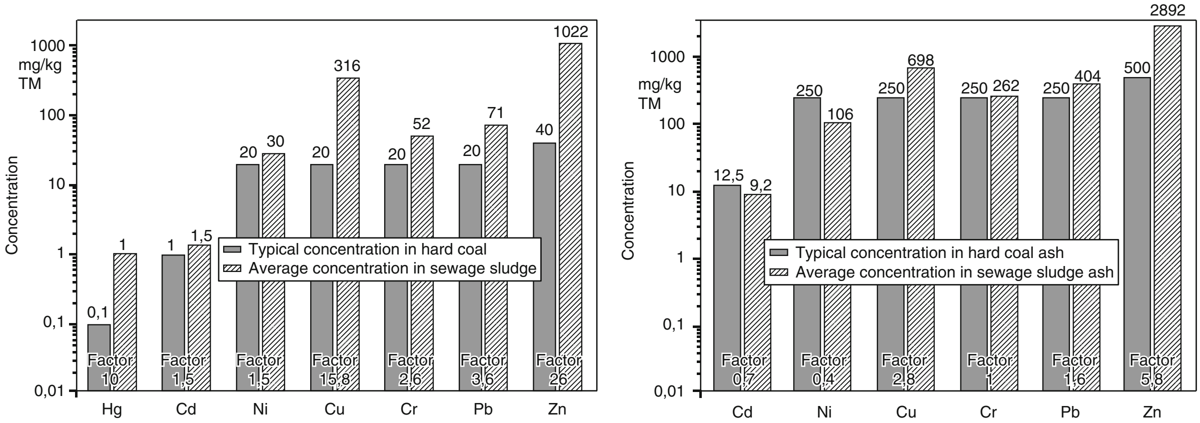
In contrast, the high ash content of sewage sludge can lead to overcharge of the electrostatic precipitator. When 5–25% thermally dried sewage sludge is co-fired with hard coal (relating to the fuel capacity), an ash quantity multiplied by the factor 1.7–4.7 must be anticipated. For a sewage sludge proportion of 5 resp. 25% for example, already 44 resp. 84% of the ash comes from the sewage sludge. This results in corresponding changes of the ash properties.

Ash utilization. The composition of the fly ash and the bottom ash of coal dust-fired systems determine the possibilities for its utilization. For example, the concentration of alkaline, sulfates, chlorides, and unburned carbon is essential for using the fly ash in the cement and concrete industry.

The co-combustion of wood is least critical due to the very low ash content. For straw, the increase of the alkaline content and of the unburned substances can limit the utilization of ash as soon as a straw fraction of 10% referring to the thermal capacity is exceeded. In addition, an increased amount of unburned straw nodes can remain, which will make the utilization of the fly ash difficult. For lignite-fired systems, however, the ash is mostly used for recultivation in open-hole mining so that appropriate measures shall ensure that specific ash substances should not leach out and enter, e.g., the ground water.

A decrease of the carbon content was observed in the fly ash with an increasing proportion of sewage sludge. Insofar, the higher ash fraction in the sewage sludge improved the fly ash product to be marketed.

Primarily, the other ingredients of the sewage sludge ash need to be considered for further assessment of the ash properties compared to the coal ash. Next to the main ingredients, first of all the substances with toxic behavior and/or accumulation behavior in the biosphere are of special interest. Despite of the given spread, however, it turns out that only very few sludges are more contaminated than this is permitted for agricultural use.



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 6
Comparison of trace elements in dry fuels (*left*) and ashes (*right*) (*TM* dry matter; according to [1])

Apart from substances like mercury, selenium, and arsenic, which as elements or in their compounds emit significant fractions via the flue gas flow due to low boiling points, most microelements from sewage sludge can be found in the solid residues of firing or flue gas cleaning. Figure 6 shows a direct comparison between sewage sludge ash and typical hard coal ash. Accordingly, the concentration of microelements in consideration of the different ash contents becomes similar. The co-combustion of sewage sludge with hard coal thus does not lead to a significant change of the pollutant concentration in the ash.

For heavy metals leaving the boiler, where the combustion takes place partly via the flue gas flow, the removal from the flue gas has to be examined in the following cleaning stages. In the wet flue gas desulfurization systems (REA) usually integrated within power plants, heavy metals are only partly removed. The remaining part is emitted via the flue gas flow into the atmosphere. For mercury, for example, a removal of approximately 50% is achieved; the rest is emitted into the atmosphere. This may require improvement of the flue gas desulfurization systems (REA) customary in power plants, for example, by specifically adapted precipitating agents or an additional downstream filter stage (e.g., activated charcoal filter). It has to be noted in this respect that different regulations apply according to the legal emission limits for coal and for sewage sludge. The latter is basically categorized as waste; in Germany, for example, the requirements of the 17. BlmSchV (17th Federal Control of Pollution Act) has to be met, which are stricter than those of the 13th BImSchV, which apply for exclusive firing of coal in conventional power plants. The European standard EN 450, amended in 2005, which regulates the utilization of fly ash as a concrete additive, now also includes fly ash from the co-combustion of fuels such as wood, straw, sewage sludge, or also paper sludge. This is valid as long as the mass fraction of the co-fired fuels does not exceed 20%, and the ash formation from the additional fuel is not more than 10%. Next to the mentioned quality requirements, further characteristics are specified in the EN 450. Thus, by the amendment of the standard, an essential obstacle was overcome for the propagation of co-combustion.

Co-combustion in Fluidized Bed Systems

Aspects of co-combustion in fluidized bed systems are discussed below (see [1–31]).

Combustion Process

In contrast to coal, biomass with its higher content of volatiles tends to post-combustion in the free space of the fluidized bed firing system (see [1–31]). This is in particular true for stationary fluidized bed systems. Furthermore, smaller, light particles (e.g., straw) can be carried out of the fluidized bed. These light particles combust within the free space and increase due to this post-combustion the temperature inside the free space.

A good mixing within a circulating fluidized bed system will evenly distribute the fire-room temperature. However, a temperature shift upward can result also here, if biomass fuels are co-incinerated.

Since fluidized bed systems are particularly suitable for fuels containing ballast, co-firing of mechanically dehydrated sewage sludge makes sense. However, this mainly serves for disposal and less for energy gain due to the low calorific value and the revenues which can be achieved. While the higher content of water of the sewage sludge increases the volume flow of the flue gas compared to hard coal, this effect is low for the co-combustion with lignite. Depending on the calorific value and on the added amount of sewage sludge, however, the thermal capacity and thus the steam production will correspondingly decrease.

On the other hand, synergy effects can result due to the co-combustion of biomass increasing the efficiency of power plant operation. For example, it has been proven in an industrial fluidized bed power plant that by the co-combustion of wood pellets and the thus resulting fine wood ash, the balance of particle size of the fluidized bed system shifted toward finer particle sizes. This significantly reduced the solid matter inventory inside the combustion chamber, leading to a reduction of the electricity demand of the power plant (i.e., the own consumption has been reduced).

Slagging and Fouling

While no additional operation problems are expected for the co-combustion of wood, solid biofuels based on herbaceous biomass can lead to increased slagging and fouling compared to coal (see [1–31]). This is particularly due to the potassium chloride contained in herbaceous biofuels.

In a circulating fluidized bed system (88 MW thermal capacity), for example, firing of coal with a sulfur content of 3% together with straw (proportion in the thermal capacity each 50%) resulted in heavy slagging within the combustion chamber in the cyclone and in the area of the superheater. After short operations time, the operating parameters could no longer be met. Afterward, only coal was used with sulfur content below 1%. The increasing melting temperatures of the ash deposits with the use of such low-sulfur fuel resulted in less slagging; slagging only occurred in the area of the superheater, where it was facilitated by the design of the superheater with narrow channels (here: 37 mm). However, this problem could be avoided to a large extent by use of suspended superheaters with a channel width of 50 mm (for the prevention of bridging) as well as lowering the flue gas temperature below the melting point of potassium chloride (770°C).

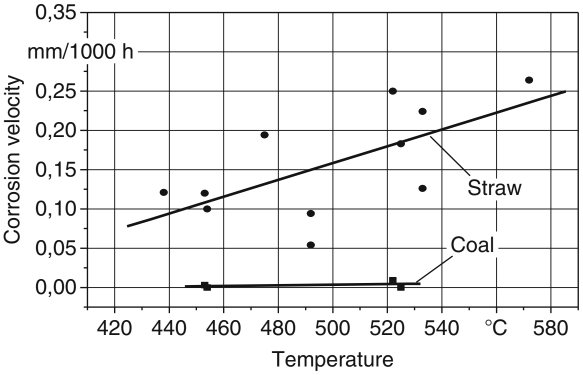
Compared to an exclusive coal firing, the fouling rate on plant components subject to flue gas contamination increases, e.g., for a straw proportion of 50% of the installed thermal capacity, the fouling rate reaches five times the value of exclusive coal firing. However, such pollution is easy to remove.

Corrosion and Erosion

Corrosion problems are not expected when wood is co-combusted in fluidized bed systems (see [1–31]). This however does not apply for biofuels produced from herbaceous biomass, particularly due to the potassium chloride contained in it.

Corrosion examinations of different materials within a circulating fluidized bed system showed significant corrosion to the convective superheater heating surfaces with the co-combustion of straw, although the test results with short test periods of 500–1,000 h are associated with a certain degree of uncertainty. When martensitic steel (X20CrMoV121) was used, the corrosion rates, for example, for co-combustion of straw were approximately 10 times higher than with exclusive firing of coal (Fig. 7). They are thus significantly higher than within a dust-firing system with the same proportion of straw. It is assumed for the reason for the high corrosion rates that the in situ desulfurization in the fluidized bed facilitates the formation of potassium chloride. This potassium chloride will precipitate on the superheater pipes and releases the corrosion-causing chlorine when potassium sulfate is formed. Also, the selection of different high-alloy steels did not result in a significant decrease of the corrosion tendency.

Different measures are taken to reduce the corrosion of the convective heating surfaces. The most important measure turned out to be the reduction of the bed temperature below 860°C. By this and other modifications, it has been achieved that after 7 years, the superheater still was in operation.



Co-combustion of Wood in Coal-Fired Large-Scale Power Plants. Figure 7
Corrosion rate for co-combustion of 50% straw in a circulating fluidized bed system versus steam temperature (according to [1])

Newer concepts therefore aim not to arrange the superheater in the flue gas tract, but as immersion heating surface within a fluidized bed cooler, and thus to utilize the characteristic of a circulating fluidized bed system. Since there may be unconsummated straw components in the cyclone return of the circulating fluidized bed, forming potassium chloride during their combustion, comparably high abrasion rates were determined with corrosion sensors arranged inside the return. If corrosion is to be prevented, it is therefore required to connect a non-cooled fluidized bed upstream of the fluidized bed cooler with superheater in order to assure burnout prior to reaching the superheater. This design has proven to be successful; however, the immersion heating surfaces eroded after several years.

Both the corrosion and emission problems as well as the mentioned slagging and fouling problems can be practically prevented best by input of correspondingly less fractions of biomass relating to the firing heat capacity (below 10%).

Emissions

The co-combustion of biomass in coal-fired fluidized bed systems mainly has the effect that emissions are reduced, except for the hydrogen chloride (HCl) emissions when straw is used (see [1–31]).

The sulfur dioxide (SO_2) emissions decrease with increasing biomass proportion in relation to the thermal capacity. This, on the one hand, is due to the lower sulfur content of the biomass compared to coal and, on the other hand, to the encapsulation of the SO_2 in the biomass ash.

For the nitrogen oxide (NO_x) emissions, the possible effects are not uniform. Tests showed that there were only small changes of the NO_x emissions with small proportions of biomass to be co-combusted. Other experiences even revealed a reduction of NO_x with an increasing biomass proportion; this particularly applies to co-combustion of wood. Tests have also shown that the N_2O emissions significantly decrease with the co-combustion of biomass.

Similar as for dust-fired systems, the co-combustion of straw causes an increase of hydrogen chlorine (HCl) emissions. In a fluidized bed system, for example, with a straw proportion of 60% relating to the installed thermal capacity, the chlorine input into the firing system was about 20 times higher than in case of exclusive firing of coal. The entered amount of chlorine can be found almost completely in the flue gas. The co-combustion of wood however leads to a reduction of the HCl emissions.

For the co-combustion of sewage sludge within a circulating fluidized bed system, the emissions of SO_2, NO_x, CO, and dust are within the legal range of fluctuation. For example, in Germany, the limit values for the application of the proportional regulation according to 17th BImSchV are therefore undercut. In order to safely meet the limit value for heavy metals (e.g., mercury) it may be required to add an additional flue gas cleaning system (e.g., fly stream absorber with lignite coke) downstream of the electrostatic precipitator.

Ash Formation and Utilization

Correspondingly, similar conclusions as for dust-fired systems apply to the accruing ash and its possibilities for utilization (see [1–31]).

As, for example, the ash proportion in the introduced sewage sludge is approximately 50% relating to the dry matter (TM), the ash quantity accruing in the fluidized bed system will significantly increase. In this process, the toxic substances contained in the sewage sludge are encapsulated inert within the ash. The only exception is mercury that is released from the boiler with the flue gas. The ash can therefore be used, e.g., for purposes of recultivation in open-top lignite mines, because, for example, in Germany the requirements of the dump category 1 of the TA (Technical Instruction) for municipal waste are met.

Berlin Case Study

A detailed analysis of the options and limits of co-combustion of solid biomass in existing coal-fired power plants was carried out for Berlin/Germany. The prepared technical analysis as well as the existing approvals for the power plants resulted in a clear decision for a co-combustion of virgin wood. On this basis, both the availability of resources and the technical consequences potentially resulting from co-combustion to the existing plants are discussed below.

Fuel Procurement

Germany is a densely wooded country. Approximately 11.1 million hectares, almost one third of the total area of Germany, is covered with forests. Due to the favorable climate, the average amount of wood produced per hectare is 3 times the amount produced, e.g., in Sweden. The annual felling in Germany steadily remains between 60 and 80 million solid cubic meters. Acting on the assumption of a bulk density of 0.6 t/m^3 and an average calorific value of 3 MWh/t, this is 126 million MW of heat energy for 70 million solid cubic meters. Thus, the heat energy of the total German annual felling would be sufficient for the electricity generation in five 1600 MW state-of-the-art large hard coal–fired power plants (57 million MWh$_{el}$). This is approximately one tenth of the demand for electric energy in Germany.

This context on the one hand makes clear the limited quantities of wood as a resource. On the other hand, it also required maximum efficiency of wood utilization. In addition, the use of wood as a raw material should be favored because of considerations of climate politics since the carbon will then be bonded in the wood products after the growth phase of the plant and is not immediately released back to the atmosphere in the form of CO_2.

Therefore, mainly rather low-grade wood (including short stubs, rotten knots) is suitable. This will be initially shredded for further processing. Thus, the co-combustion primarily focuses on wood from landscape conservation, scrap wood, rolled lumber, wood affected by bark beetles and thinning material from short rotational plantations, and similar types of wood. Wood, which can be used as a raw material, is out of question often also for reasons of costs.

In addition, it should be observed for the mentioned low-grade types of wood basically suitable for co-combustion that brushwood, leaves, needles, and roots should remain in the forest for the formation of humus, in terms of sustainable forestry. However, there are special cases (e.g., leaves from parks or streets), where energetic utilization may be considered. Subject to the ancillary conditions mentioned here, an approval for the coal-fired power plants in Germany should be assumed according to the legal frame conditions for waste and similar combustible substances.

Due to the relatively low calorific value and partly high water content of the firewood, which basically would be suitable for co-combustion, only short transport distances can be economically reasonably realized. Even if the economic efficiency of firewood for co-combustion is supported by saving of CO_2 certificates, this advantage is in contrast with the high specific transport costs per ton of fuel for overland transportation. One individual lorry with two 38 m^3 containers with approximately 18–20 t of wood cannot compete against the specific costs of large-scale technology, for example of lorries, with 7,000 t of oil or huge conveyor lines from the nearby open-top mining with almost 1,000 t/h of lignite. Long transport distances therefore are generally economically conceivable for energy sources with a high-energy density and good-handling properties (e.g., oil, hard coal). This however also applies to wood pellets.

Technical Solutions

The coal boilers available in Berlin/Germany are designed as dust-firing systems. A fast and fully combustion of the coal dust particles is achieved with the coal grinded to dust. The wood co-combusted within this boiler needs to be of appropriately small size, which places increased requirements to wood processing compared to grate firing.

In order to meet this requirement with respect to the size of the woodchips, a two-stage strategy is pursued for the three coal-fired combined heat and power plants used and/or designed for co-combustion. The wood is initially shredded to approximately 40 mm delivery size, and then there is another grinding process to lengths of several millimeters within the particular hammer mills of the power plants.

For this technology of joint milling of the coal–woodchips mixture, the grinding and feeding into the boiler is the main problem of the co-combustion within these power plants. The reason lies in the different fuel properties of hard coal and wood.

- On the one hand, wood has a significantly larger volume relating to the calorific value compared to hard coal. The result is that the amount of wood is limited which maximally can be conveyed through the coal mills. For a proportion of 5% of the thermal boiler capacity, the total fuel volume increases by up to 30–40%.
- On the other hand, the proportion of moisture and volatile substances in wood is larger than in hard coal. The larger content of moisture requires more intense drying of the mixture and leads to higher flue gas losses. In addition, for the co-combustion of wood, there is an increased risk that the wood components will already ignite before they enter into the mill due to the higher content of volatile matters. There also is an increased risk of slagging in the combustion chamber due to the lower melting point of the wood ash, which at least in the slag-tap furnace of one of the Berlin power plant is beneficial for the slag removal from the boiler.

These issues shown here were tested in the Reuter C hard-coal power plant in several test series with an electric capacity rating of 132 MW, and technical solutions were found for the co-combustion of wood (e. g., by a reduction of the sifter temperatures in front of the mills).

An addition, the effects of co-combustion of wood of up to 5% of the fuel heat for the efficiency of the boiler in Reuter C has been examined. A maximum loss of efficiency of 0.25% has been measured for wood with a moisture content of 50%. This however can be assessed as very low.

Due to the longer holding times of the fuel in fluidized bed systems, higher co-combustion rates than 5% of wood are possible there. A direct supply of the wood into the boiler, i.e., no longer via the hammer mills, can here open up new dimensions for the co-combustion of wood.

Economic Efficiency

The economic efficiency of the co-combustion of wood is mainly influenced by the price of wood as a fuel, the price of the coal replaced by the wood and the costs for the CO_2 certificates as well as the additional investment costs and operating costs for the co-combustion of wood. The main cost factor of the co-combustion in this process is the costs for the fuel itself. These costs roughly are broken down into the actual price of wood as well as the shredder and transport costs. For preferential use of wood from landscape conservation from the close vicinity, the prices of wood and transport accordingly are moderate, and the highest costs result from the mobile shredder equipment on location. These shredder costs however can be reduced to approximately two thirds with stationary electric shredders; for economic reasons, however, a fixed location and larger quantities of wood is required.

The other important economic parameters such as the market prices for electricity, heat, and the efficiency of the power plant play the important part in the resource planning of the power plant; it is decided here whether it is economically worthwhile to operate of shut off a power plant in a specific market situation. The co-combustion of wood to the amount of 5% of the thermal capacity has only small influence to this. But the economic efficiency of the co-combustion of wood is adversely affected by longer standstill periods of the combined heat and power plants, in particular outside the heating period, because then less wood can be co-combusted.

At the end of 2009, for example, the following circumstance has been observed. The price of hard coal declined to approximately half the price compared to fall 2008. At the same time, the price for CO_2 certificates declined by approxiamtely one quarter compared to the end of 2008. In contrast, the price of wood declined only to a small extent. The forest owners practise retentiveness with felling when the prices for wood are going down and wait for a higher price level.

For wood from landscape conservation, however, the price remained stable with slightly reduced shredder and lorry transport costs depending on the oil price. Therefore, the economic situation of the co-combustion of wood in hard-coal fired power plants in Germany changed to the worse in 2009 compared to 2008, but slightly recovered again in the year 2010.

Conclusion

The co-combustion of biomass is an option for a relatively efficient production of electricity out of large quantities of biomass. Against this background, the goal of this paper is it to analyze these options and to examine them by means of a case study. The issues explained can be briefly summarized as follows.

- Basically, a multitude of different types of biomass can be used in existing coal-fired power plants. Recently, quite different technical solutions were realized.
- There should be no basic technical problems as long as the proportion of the biomass used in relation to the coal is small, and this does not significantly change the properties of the coal with regard to combustion.
- Nevertheless, co-combustion of wood in coal-fired power plants requires individual technical solutions depending on the unloading situation, on the type of mill and boiler, as well as on the location of the power plant. Generally, appropriate solutions can be found, as indicated by the development in some European countries in the past years.

All in all, the co-combustion is a technically promising option for the large-scale highly efficient production of electricity from biomass by the substitution of an energy source with relatively high specific greenhouse gas emissions. This efficiency can even be improved by co-combustion in combined heat and power plants.

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